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ARMY MEDICAL RESEARCH LABORATORY

FORT KNOX, KENTUCKY

PROJECT NO. 1 - Cold Weather Operations

Sub-Project No. 1-1, Test of the Adequacy and Ranges of Use of Winter Combat Clothing.

2 June 1944 NOFORN

RESEARCH AND DEVELOPMENT DIVISION
OFFICE OF THE SURGEON GENERAL
DEPARTMENT OF THE ARMY

ARMORED MEDICAL RESEARCH LABORATORY
Fort Knox, Kentucky

Project No. 1-1
727-1 SPMEA

2 June 1944

1. PROJECT NO. 1 - Cold Weather Operations. Sub-Project No. 1-1 Test of the Adequacy and Ranges of Use of Winter Combat Clothing.

a. Authority - Letter Commanding General, Headquarters Armored Force, Fort Knox, Kentucky, File 400.112/6 GNOHD, dated September 24, 1942.

b. Purpose - To determine: (1) The protective value of Arctic issue clothing for resting men exposed to still air at -18° to -40°C, and (2) describe the thermal and subjective experiences of a large group of men dressed in subject clothing at these temperatures.

2. DISCUSSION

a. Considerable attention has been focused upon insulation requirements in the design of cold weather clothing. The objective has been to provide sufficient protection against heat loss to insure the maintenance of temperature within acceptable limits over the desired exposure period. On the assumption that the normal comfort state of man should, if possible, be maintained, the insulation required at a given sub-zero temperature, relative to that provided for comfort in a normal environment has been [illegible] pre-dictions have been made concerning the probable thermal experience of the wearer at other exposure temperatures, both with respect to his maximum drop in temperature and his rate of cooling.

b. The subject Arctic issue assembly represents, to a high degree, the principal of incorporating maximum insulation into such protective clothing. For a complete description of its protective capacities, it should be known at what minimum temperature the clothing will permit prolonged exposure without significant loss of body heat or drop in average skin temperature. The probable thermal experience of the wearer at any lower temperature should also be known.

c. Objectives of the present study were to compare the thermal characteristics of the subject clothing with the performance predicted by its insulation value and to determine the degree of variability in thermal and subjective response among subjects dressed in the clothing and exposed for three (3) hours at sub-zero temperature.

d. Details of test procedures and the results will be found in the Appendix.

3. CONCLUSIONS

a. The permissible exposure time without serious discomfort for the average resting men at $-26^{\circ}C$ is less than three (3) hours.

b. The subject clothing has an inherent insulation value under equilibrium conditions of 5.0 clo, which is sufficient, according to theoretical calculations, to maintain average skin temperature continuously without change at an ambient temperature of $-19^{\circ}C$ (Metabolic rate = 70 Cal/M^2/hr.).

c. The apparent insulation provided by the clothing was not constant during exposure but increased from 2.8 to 4.4 clo during three hours at -23° to $-29^{\circ}C$ air temperature. This resulted in a rate of cooling for this exposure period approximately six times faster than anticipated by the standard calculations.

d. The insulation value of the clothing, as expressed by the standard clo index does not, according to present findings, provide a complete measure of the thermal properties of the clothing, nor does it successfully predict the behavior of men wearing the clothing.

e. Two indices are proposed for describing the thermal behavior of Artic clothing; the cooling constant, k, and the equilibrium temperature, θ_e.

4. RECOMMENDATIONS

No specific recommendations are made. Attention is called to the practical finding of this study that the thermal experiences of subjects dressed in Arctic issue clothing are not in accord with the predicted behavior and, as a consequence permissible tolerance time was found to be markedly less than anticipated. The basic reasons for this departure from anticipated results requires further investigation by clothing designers.

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2 Incls:
#1 Appendix, with eight tables
#2 Figures 1 to 10, inclusive

APPENDIX

I. EXPERIMENTAL PROCEDURE

During a study of the subjective responses of a representative sample of men exposed to low temperature, data on the thermal changes were obtained in forty-one (41) of the seventy-nine (79) subjects, all dressed in the subject clothing. These men were troops who had had several months of military experience beyond their basic training. The seventy-nine men were examined in eight (8) groups of approximately ten men each. Each group was under test for three (3) days, a new group arriving on successive Monday and Thursday mornings. They were exposed in the cold room to still air at an ambient temperature of -23° to -29°C for the same length of time and at the same time in the morning.

The Arctic clothing worn by the subject was fitted as carefully as possible. The garments worn were:

Underwear, wool 50/50	Socks, Wool, Cushion sole (1 pair)
Trousers, Field, pile	Socks, Wool, Ski (2 pair)
Trousers, Field, Cotton, O.D.	Shoe, Felt (Alcan)
Jacket, Field, pile	Mukluk, with burlap insole
Parka, Field, pile	Mitten, insert, trigger finger M-1943
Parka, Field, Cotton, O.D.	Mitten, shell, trigger finger M-1943

No measurements were made during the first morning exposure, the men being allowed to sit quietly for the required three hours. During the remaining two (2) days of the test, skin temperatures were obtained on five points for four (4) members of each group. A fifth subject had temperature measurements made on ten points of his body and oxygen consumption was measured for the entire period with a five minute break at the end of each hour.

Additional data are presented on a group of two (2) men and on another group of four (4) men who were repeatedly studied for periods of approximately three (3) weeks each at the same ambient temperatures, and dressed in the same clothing. A few additional studies were made at -18°C and -40°C.

The mean skin temperature was obtained from the five measured points according to the following weighting scheme; chest 0.30; thigh 0.30; arm 0.16; calf 0.18 and toe (or foot) 0.06. The standard method was followed in the calculation of clo values and in addition, a new procedure was employed to determine the final insulation value of the clothing from the equilibrium skin temperature. This method is discussed below.

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II. RESULTS

1. Thermal Changes:

The insulation provided by the Arctic clothing was found to be inadequate to maintain thermal balance under the conditions of test (resting subject, air temperature -23° to -29°C no air movement). Over a three (3) hour period of exposure all subjects lost heat steadily, as indicated by decreases in both surface and deep body temperatures. Average temperature response curves are shown in Fig. 1, and the thermal changes experienced by the forty-one (41) subjects are summarized in Table 1. It will be noted that the degree of cooling was greatest during the first hour and that, by comparison, relatively little change occurred in the third hour. Some of the subjects even experienced increases in rectal or skin temperatures, or both, after two hours of cooling. As expected, the greatest change among the recorded skin temperatures was in the extremities (toe or finger), followed in order by calf, thigh, arm and chest. It is of interest to note that toe temperatures below 0°C were observed in ten (10) subject exposures.

These changes in temperature reflect the loss of body heat and indicate that the overall insulation afforded by the clothing was insufficient to offset the high skin-air temperature gradient so that the rate of heat transfer to the environment was greater than the rate of heat input (metabolism). The records of total heat exchange in nine (9) subjects are summarized in Table 2. In keeping with the temperature changes, the calculated loss of body heat was markedly greater during the first hour than subsequently, the excessive cooling being offset to some extent in the second and third hours by the greater metabolic rate, which increased an average of 40% from the first to the last hour. Of the total heat transferred to the environment, that lost from storage constituted some 54%, 31% and 13% during the three successive hours. It is evident from these data and from the temperature response curves (Fig. 1) that the adjustment toward a new thermal state was rapid.

TABLE 1

SUMMARY OF THERMAL CHANGES DURING 3 HOURS EXPOSURE

Ambient Temperature -23° to -29°C; 41 subjects

Temperature	Temperature, °C, at end of stated exposure time, hours							
	0		1		2		3	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Rectal	37.54	36.67-38.00	37.13	36.19-37.50	36.73	35.45-37.11	36.63	35.67-37.51
Chest	33.6	29.6 -36.8	33.5	28.0 -36.7	33.2	28.0 -36.2	33.0	28.8 -36.7
Mean Skin	32.8	30.7 -34.3	28.4	23.0 -31.2	26.4	22.4 -29.6	25.7	20.2 -29.1
Toe	27.8	20.1 -35.7	16.0	2.0 -28.8	7.6	-2.5 -19.0	5.2	-3.4 -13.4

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TABLE 2

SUMMARY OF TOTAL HEAT EXCHANGE DURING THREE HOURS EXPOSURE

Ambient Temperature -23° to -29°C; Nine Subjects

(All values in $Cal/M^2/hr$)

HEAT	Hour					
	1		2		3	
	Mean	Range	Mean	Range	Mean	Range
Input (metabolism)	50.6	43.3-61.2	60.6	44.5-85.5	71.0	54.5-96.2
Output - total	111.0	75.6-143.3	91.0	64.9-112.9	79.5	61.3-99.5
Output - by resp. and evap.	17.6	9.2-21.8	19.4	12.1-25.5	21.3	12.4-37.3
Output - from storage*	60.7	30.2-100.0	30.4	2.8-63.2	8.8	0.0-43.3
% Total Output from storage	54.3	40.0-69.8	31.0	3.3-57.9	13.3	Neg. -39.8

*Mixing Coefficient = 2/3

2. Variability Among Subjects.

Variability in thermal behavior among the subjects was marked and appeared to be characteristic of the individuals since closer agreement was obtained in repeated tests on a given subject than from one subject to another. The frequency distributions for mean surface temperatures and toe temperatures at the end of the second and third hours of exposure are shown in Figs. 2 and 3, each subject being represented, in general, by two test values. In contrast to the wide variability exhibited in these histograms, the results of repeated tests on two subjects revealed a maximum spread of only 4.5°C for the mean skin temperature and 5.6°C for the toes after equal periods of exposure. Owing to this wide range of behavior among subjects, it is evident that the evaluation of clothing in terms of the absolute thermal changes at low temperatures may be misleading when based upon observations on a small number of subjects.

3. Subjective Responses.

The subjective reactions of the 41 resting subjects, all dressed alike, and exposed to approximately the same ambient temperature have been

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discussed in detail in another report*. It was shown that among the group there were significant differences in time of response to cold exposure and that the subjects could be separated, in this respect, into three relative categories of susceptible, intermediate and resistant. No correlation was found, however, between relative resistance and thermal changes. The group will be considered as a whole, therefore, in the present discussion of subjective experiences.

The duration of exposure up to the time of onset of stinging or pain in the extremities and the toe temperature at that time are summarized in Table 3. In thirteen subject exposures no pain or stinging in the feet was experienced during the entire period of exposure. The records of exposure time prior to the onset of shivering and the parallel mean surface temperatures are also summarized in the table. The data are characterized by a considerable degree of variability, as shown in Figures 4 and 5, and one must resort to statistical averages in describing the limitations of the clothing under test. Insofar as the subjective reactions here considered determine the acceptable period of exposure, the distribution as shown in Table 3 may be expected among a group subjected to an ambient temperature of -23° to -29°C.

4. Insulation Value of Clothing.

Metabolic rates were recorded on seven subjects during two tests, in 4 and 6 tests on two subjects and once on a ninth man. From these measurements, together with the records of temperature change, the insulation value of the clothing was calculated in the standard manner. The

TABLE 3

DISTRIBUTION OF SUBJECTIVE RESPONSES AND COINCIDENT TEMPERATURES

Percent of Group	Exposure time to onset of pain in toe	Toe Temp. at onset °C	Exposure time to onset of shivering	Mean Skin Temp. at onset
25	100 min or less	10.0 or higher	91 min or less	28.7°C or higher
50	121 min or less	7.5 or "	124 min or less	26.9 or "
75	150 min or less	5.0 or "	157 min or less	25.7 or "
90	180 min or less	2.5 or "	180 min or less	24.7 or "

*Project No. 1. Cold Weather Operations, Sub-Project No. 1-1, Test of the Adequacy and Range of Use of Winter Clothing and Sub-Project No.~~1~~-18, Study of the Method of Selection of Men for Cold Weather Operations, 10 April, 1944.

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results are summarized, for the first, second and third hours separately, in Table 4. The average clo value for the second and third hours is taken, in the standard method, to represent the insulation of the clothing. Accordingly, the present clothing is found to have a clo value of 4.0, equal to a total conductance of 1.17 $Cal/M^2/Hr/^oC$ for still air conditions. From this we find that with a metabolic rate of 70 $Cal/M^2/Hr$– (for 3rd hour in present tests), the clothing should maintain thermal balance at an ambient temperature 43^oC below the average skin temperature, or with an exposure temperature of -26^oC, the skin should cool toward an equilibrium mean temperature of 17^oC. An examination of the actual records, however, indicates that the average equilibrium mean skin temperature, predicted from the trend of the cooling curves was 25.7^oC rather than 17^oC, as calculated.

It is of interest to note that the calculated insulation value increased with exposure from an average of 2.8 clo during the first hour to 4.4 clo during the third. Examination of the data revealed a relationship between the hourly clo value and the portion of total heat output contributed from storage during the hour. The association is shown in Figure 6. It is evident from this that the insulation, as presently determined, is subject to considerable variation, depending upon how far the subject is from thermal equilibrium at the time for which the calculation is made.

TABLE 4

INSULATION VALUE OF CLOTHING

In Clo Units, Calculated by Standard Method
Ambient Temperature, -23^o to -29^oC; Nine Subjects

	First Hour	Second Hour	Third Hour	Average (Second and Third Hour
Mean	2.8	3.6	4.4	4.0
Range	1.7 - 4.4	2.1 - 5.3	2.9 - 5.9	2.1 - 5.9

The thermal relationships assumed in the standard calculations are basic and may be safely applied to a relatively simple thermal system which is in balance, or approximately so. They are not general enough in form, however, to describe the behavior of a complex system such as man and clothing, during the cooling period before equilibrium is reached. In the present study observations were limited to this cooling period with attendant rapid thermal changes. There are a number of factors operating during this period which are not fully considered in the standard calculations. Not only do changes take place in the heat content of the body but the distribution of heat within the body is also changing. There are concurrent changes in the

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heat content of the clothing which are not considered in the calculations. Moreover, because of the marked differences in thermal protection of the extremities as compared with the torso, the relative amounts of heat escaping from the various parts of the body undergo change during the cooling period. The proper weighting of skin and rectal temperatures in order to calculate the loss of heat from storage may also be subject to question.

In recognition of the uncertainty of calculating thermal changes early in the exposure period, the standard method of determining the clo value disregards the results from the first hour. The data presented here suggest, however, that this may not be a sufficient safeguard since the calculated change in body heat content is significantly high in the second and even in the third hour of exposure. In order to minimize error from this source in the determination of insulation value, it would be desirable to continue the exposure period until the new equilibrium level for the system--man and clothing--is established, so as to eliminate the uncertainties of the changing state. Because of the intervention of discomfort, this could not be done at the exposure temperatures employed in the present study. The data obtained do, however, permit an approximation of the desired condition in two ways: First, an estimate of the insulation value, without considering the uncertain heat debt factor, is obtained from the curve in Fig. 6, from which the clo value for zero change in body heat content is found to be 5.0. Secondly, from the trend of the mean skin temperature curve, it is possible to predict its asymptote; that is, the equilibrium level toward which the skin temperature is cooling. The insulation index is obtained directly from this value and the metabolic rate (taken in the present calculation as the third hour value) and again, the heat debt factor does not appear in the calculation. The clo value is given by the following equation:

$$I_c = \frac{5.5\ \theta_e}{M - (E + A)} - I_a$$

where θ - predicted equilibrium temperature, above ambient
M - metabolic rate during 3rd hour
I_c - clothing insulation
I_a - insulation value of air
$E + A$ - heat loss by respiration and evaporation

The equilibrium temperature, θ_e, is obtained from the mean skin temperature curve by direct calculation, on the assumption that the latter has the form and characteristics of cooling curves generally. The cooling equation may be written:

$$\frac{\theta_s - \theta_e}{\theta_o - \theta_e} = e^{-kt}$$

where $\theta_e = \dfrac{H}{AC_t}$

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and θ_s = skin temperature, in excess of ambient, at time
θ_o = skin temperature, in excess of ambient, at zero time
θ_e = skin temperature, in excess of ambient, at equilibrium
k = cooling constant
A = surface area
C_t = heat conductance
H = rate of heat input

We may also write, from the foregoing equation:

$$\theta_e = \frac{\theta_1 \times \theta_3 \times \theta_2^2}{\theta_1 + \theta_3 - 2\theta_2}$$

where, θ_1, θ_2 and θ_3 are skin temperature levels (above ambient) evenly spaced in time, i.e., $t_2 - t_1 = t_3 - t_2$. By means of this relationship, θ_e was predicted and from the resulting values and 3rd hour metabolic rates, the insulation value of the clothing calculated, as shown in Table 5. The average clo value of 5.1 agrees closely with the value of 5.0 estimated from Fig. 6. For a metabolic rate of 70 Cal/M^2/Hr., this degree of insulation is theoretically capable of maintaining continuous thermal balance in an environment of -19°C. At an ambient of -26°C, the wearer would experience a maximum drop in average skin temperature of 7°C rather than 15°C, as predicted from the standard clo value. The anticipated drop of 7°C agrees with the observed decrement of 7.1°C in three hours. It is evident that the elimination of the uncertain heat debt factor from the calculation results in a better estimate of insulation.

TABLE 5

PREDICTED EQUILIBRIUM TEMPERATURE
AND INSULATION VALUE, CALCULATED FROM θ_e

	θ_e*	Clo
Mean	51.0	5.1
Range	43.9-55.3	3.7-7.0

* Above ambient

5. Rate of Cooling:

With the assumption that the insulation value of clothing remains constant with exposure, it is possible to calculate the anticipated loss of body heat over a given period of time at a selected environmental temperature. Thus, with 5.0 clo and 60 Cal/M^2/Hr.*, the calculated rate of heat loss from storage with an ambient of -26°C, is found to be 12.0 Cal/M^2/Hr.,

* Average for three hours in this study.

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or 36.0 Cal/M^2 for 3 hours exposure. This, for a 70 kilo man, is equilivant to a drop in average body temperature of 1.1°C, which, if assigned entirely to a change in skin temperature, would amount to a decrement of 3.3°C (a=2/3). Any allowance for decrease in rectal temperature, would, of course, reduce the anticipated lowering of skin temperature. These predictions are in sharp contrast to the actual thermal experiences here reported. Thus, the average heat debt at the end of 3 hours exposure was 100 Cal/M^2 or 2.75 times greater than the predicted value. The drop in average skin temperature amounted to 7.1°C while the deep body temperature decreased 0.91°C. In other words, there was no relationship between the observed rate or amount of thermal change and the values predicted from the heat transfer capacity of the clothing, as described by the clo value. This is not surprising in view of the fact that the apparent insulation value of the clothing, contrary to the assumption in the foregoing calculation, was not constant from hour to hour.

6. Discussion

The demonstrated failure of the insulation index to predict the cooling rate clearly shows its limitations as a useful criterion of clothing characteristics with respect to low temperature exposures. Of greater practical significance, however, is the apparent change in insulation with exposure which suggests that the inhrent protective quality of the garments is not being fully utilized from the start. As a result, clothing which should be acceptable for prolonged exposure is actually satisfactory for less than 3 hours. A drop in skin temperature of 7°C, which was experienced in three (3) hours in the present studies, for example, would not be expected with full utilization of the inherent insulation from the start, for a matter of eight (8) hours. This difference in actual performance from the predicted, changes the evaluation of the clothing from adequate to inadequate for the exposure temperature under consideration.

In view of the considerable effort that has gone into the development of Arctic clothing with high insulation value, it is essential that the noted discrepancies in thermal behavior of the subject clothing, be explained. It is necessary to know whether or not the apparent failure of inherent insulation to be utilized early in the exposure is real and the reason therefor since further improvement in clothing design is dependent upon this knowledge. To emphasize the point, it may be stated that greater potential improvement could be secured by full utilization from the beginning of exposure of the insulation now provided than by the addition of more insulation within practical limits of bulk and weight.

Several possible explanations of the apparent change in thermal protection during exposure may be suggested for consideration. In the first place, the variation may not be real, but rather the result of limitations inherent in the method of measurement and calculation. As pointed out earlier, owing to the rapid changes in thermal state during the initial three (3) hours of exposure, the simple equation for heat exchange does not rigidly apply.

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Skin temperature measurements and the calculated mean temperature may be in error because of the rapidly changing thermal gradient. The calculated heat debt factor is also subject to error. The mixing coefficient "a" undoubtedly changes with cooling and, moreover, the present method of calculating the body heat change, does not take into consideration the relative heat capacities of the various parts of the body, which differ markedly from the relative surface areas. Another aspect which increases the complexity of the problem is the fact that the insulation provided for the extremities by the Arctic ensemble is very much less than for the rest of the body. The effect of this has been calculated to reduce the overall insulation to one half of that provided by the body clothing alone*. The significance of this becomes clear when it is recalled that it is the extremities which undergo greatest change, both with respect to surface temperature and rate of heat input during the cooling period. The changes in torso temperatures (deep body and surface) are relatively minor compared with those occurring in the arms and legs (Fig. 1).

Insofar as possible actual variation in heat conductance of the clothing is concerned, two factors which could alter the heat transfer capacity may be mentioned: first, the insulation value of clothing is determined not by its thickness alone but also by the degree of immobilization of the air trapped in the garments. Any movement within the air layer which is set up by convection, by exchange with outside air or other means would decrease the insulation. The possible order of magnitude of such change is indicated by the following conductance values:

Completely static layer of air, one inch thick - 0.7 Cal/M^2/Hr.,
One-inch air gap with free internal convection - 2.0 Cal/M^2/Hr.

The three-fold variation in conductance from complete immobilization of the air layer to free convection is greater than the three (3) hour change in insulation observed in the present study. It remains to be demonstrated whether or not any such change in conductance arising from convection, does take place in Arctic clothing during exposure.

A second factor which may act to alter the heat flow capacity of clothing is the transfer of moisture, which is always held in varying amounts by fabrics. The evaporation of water from inner garments and subsequent condensation in outer layers of clothing would result in the effective transfer of heat from the wearer to the outside. This action would be independent of conductance and not necessarily accompanied by an absolute change in weight of the clothing. The weight of water which by evaporation would account for the excessive heat transfer observed during the three (3) hour exposure is of the order of 100 gms. Compared with the quantity of water normally held by clothing in moisture equilibrium with the laboratory atmosphere, this is small, as shown by the data in Table 6. The effect of heat

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* Climatic Research Laboratory Report No. 76, Thermal Insulation of Cold Weather Clothing and Footgear, 15 April 1944.

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transfer by evaporation is shown in Fig. 7. The behavior of well-dried clothing in initial thermal equilibrium with the laboratory air did not differ markedly from that of the clothing in complete equilibrium with the atmosphere of the laboratory (moisture as well as temperature) at the start of exposure. Neither the rate of cooling nor the predicted equilibrium temperature, θ_e, was significantly altered. It is of interest, however, that there was improvement in subjective response which may be accounted for by the marked reduction in the cooling rate of the toe when the pre-dried clothing was worn.

TABLE 6

MOISTURE CHANGES IN ARCTIC CLOTHING

Wgt. dried clothing	7.43 kg.
Wgt. Clothing in moisture equilibrium with laboratory atmosphere	8.11
Wgt. moisture in clothing in laboratory atmosphere	0.68
Moisture pickup in dried clothing after 3 hours worn in cold room	0.22

The influence of initial thermal condition of clothing upon its protective behavior is further demonstrated by the relative experiences in clothing in equilibrium at the outset with the cold room and the laboratory atmospheres respectively, as shown in Fig. 7. Owing to the immediate heat drain imposed by the cold clothing, the cooling rate is markedly increased and some 80% of the 3-hour drop in mean skin temperature is accomplished in the first 15 minutes. The rate of cooling of the extremities was similarly increased and there was a corresponding decrease in exposure time to the onset of discomfort in the extremities when the subject dressed in pre-cooled clothing.

7. Analysis of cooling rates

In view of the failure to predict the actual cooling rate from the overall insulation value of the clothing, it is desirable to describe the rate of change in temperature by a simple graphical or mathematical technic. Returning to the general equation for cooling curves (Section 4), the exponential constant, k, provides such a mathematical index of cooling rate which is readily obtained graphically from the observed skin temperatures. The cooling equation may be written:

$$\log \frac{\theta_s - \theta_e}{\theta_o - \theta_e} = -k \log e.t.$$

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It is evident that this relationship yields a straight line on semilogarithmic grid paper when $\theta_s - \theta_e$ is plotted (on the logarithmic scale) against time. The slope of this line is equal to the cooling constant, k, and may be obtained graphically from the line of best fit drawn through the plotted points. An illustrative example is shown in Fig. 8. The straight line relationship was satisfactory in most instances in the present study, the departures usually occurring at the beginning or end of the exposure period.

The frequency distribution of k values thus obtained is shown in Fig. 9. The variability in k was great, exhibiting more than a ten-fold range. The median value is found to be 0.58 with one-half of the values between 0.48 and 0.85. The test-retest agreement for a given subject is fair, as shown in Fig. 10, one-half of the pairs of values agreeing with 25%, which may be compared with the ten-fold range for the entire group. On two subjects, repeated tests gave k values which differed from their averages by a maximum of 35%.

With a median k value of 0.58, it is readily shown that approximately 63% of the total drop in mean skin temperature from its initial value to the ultimate equilibrium level occurs in $\frac{1}{k}$ = 1.7 hrs. (100 min.) and 83% is accomplished in three (3) hours. The marked difference between this actual cooling rate and that predicted from the assumed constant heat transfer capacity of the clothing has already been considered.

The cooling curves for the extremities followed the same pattern as for the mean skin temperature. For example, k values, determined in the same manner, were obtained for toe temperature, with the results shown in Table 7. The median value, it will be noted, is not greatly different from that for the mean surface temperature.

The graphical analysis of time-temperature curves employed here provides a direct method of describing in simple terms the thermal behavior of subjects dressed in Arctic issue clothing and exposed to low temperatures. It involves the experimental determination of two indices: the cooling constant, k, and the clo value calculated from the equilibrium temperature, θ_e. The degree to which one may predict thermal behavior at exposure temperatures other than the one employed in the experimental determination of θ_e and k is indicated in Table 8. A slight increase in the values of k and clo with decreasing ambient tmperature will be noted, but the differences are not great. Of greatest interest is the marked increase in θ_e. This is a reflection of the greater metabolic rates at the lower temperatures, which increased sufficiently to maintain the actual mean skin temperature at the same level for all three exposure temperatures. With proper allowance made for this, it appears possible to predict with some success the thermal experience at any desired exposure temperature from the indices obtained at another temperature.

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TABLE 7

COOLING CONSTANT AND EQUILIBRIUM TEMPERATURE

OF GREAT TOE

Ambient Temperature, -23° to -29°C; 41 subjects

	k, Cooling Constant	θ_e,* Equilibrium Temperature, °C
Median	0.877	27.6
Range	0.439 to 1.729	18.0 to 36.6°

* Above ambient

TABLE 8

THERMAL CHARACTERISTICS OF ARCTIC CLOTHING AT

DIFFERENT EXPOSURE TEMPERATURES

INDEX	EXPOSURE TEMPERATURE		
	-17.8°C	-23.3°C	-36.6°C
k, cooling constant	0.617	0.770	0.880
θ_e, above ambient, °C	43.2	48.2	59.9
*Net metabolic rate, 1st hour	34.3	36.2	35.3
*Net metabolic rate, 3rd hour	38.6	45.2	59.5
% increase in metabolic rate	13	25	68
Clo, from θ_e	5.4	5.2	4.8
Mean θ_s, end 3rd hour, °C	25.8	25.3	25.0
Predicted Final θ_s, °C	25.3	24.1	23.3

* Net metabolic rate = M-(E+A), Cals./M^2/Hr.

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FIG. 1

AVERAGE THERMAL CHANGES DURING 3 HOUR EXPOSURE TO AMBIENT TEMPERATURE OF -23 TO -29° C

41 SUBJECTS

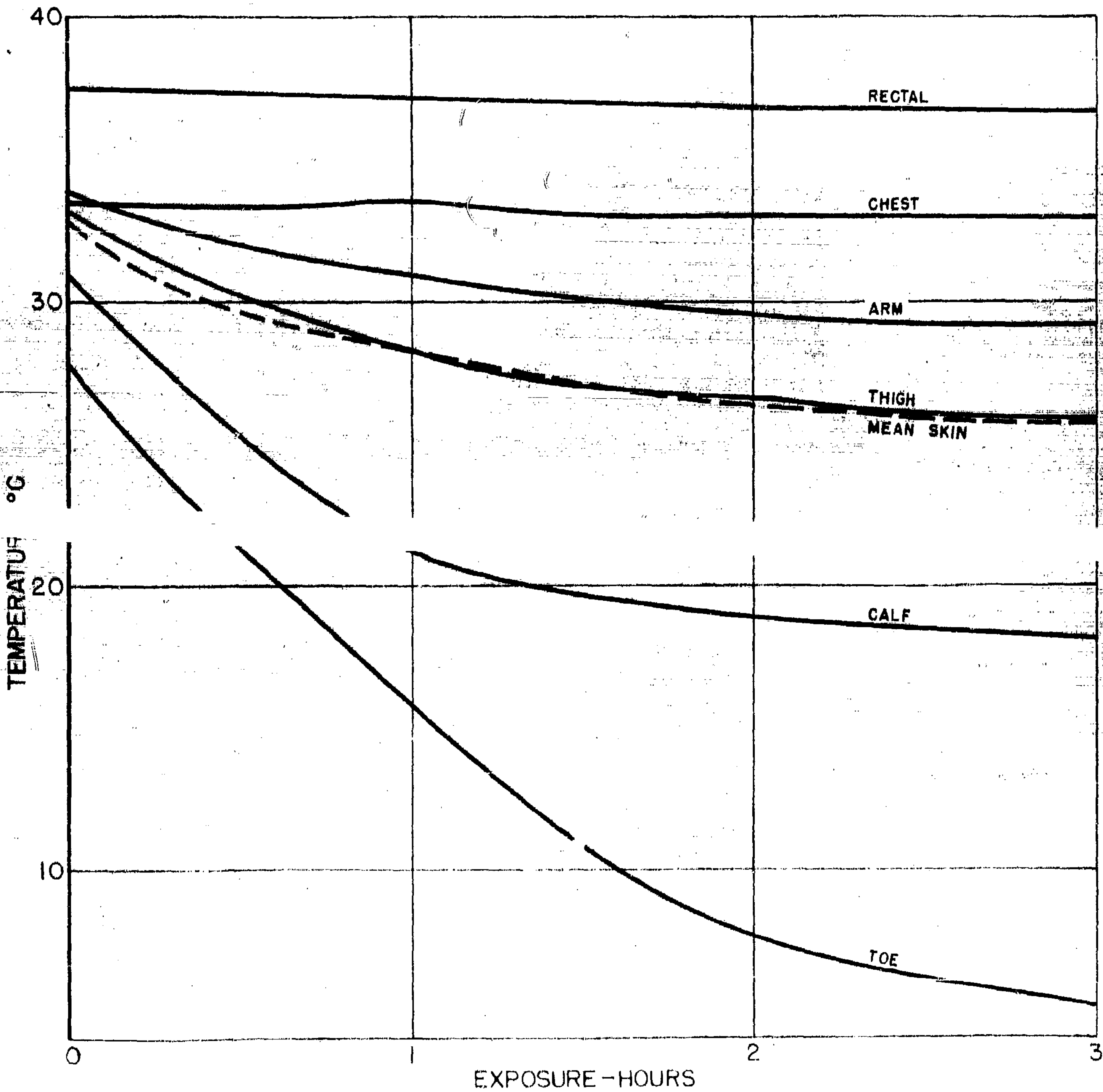

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FIG. 1

FIG. 2

DISTRIBUTION OF MEAN SKIN TEMPERATURES
AT END OF 2 ND AND 3 RD HOURS EXPOSURE

AMBIENT TEMPERATURE -23° TO -29° C

41 SUBJECTS

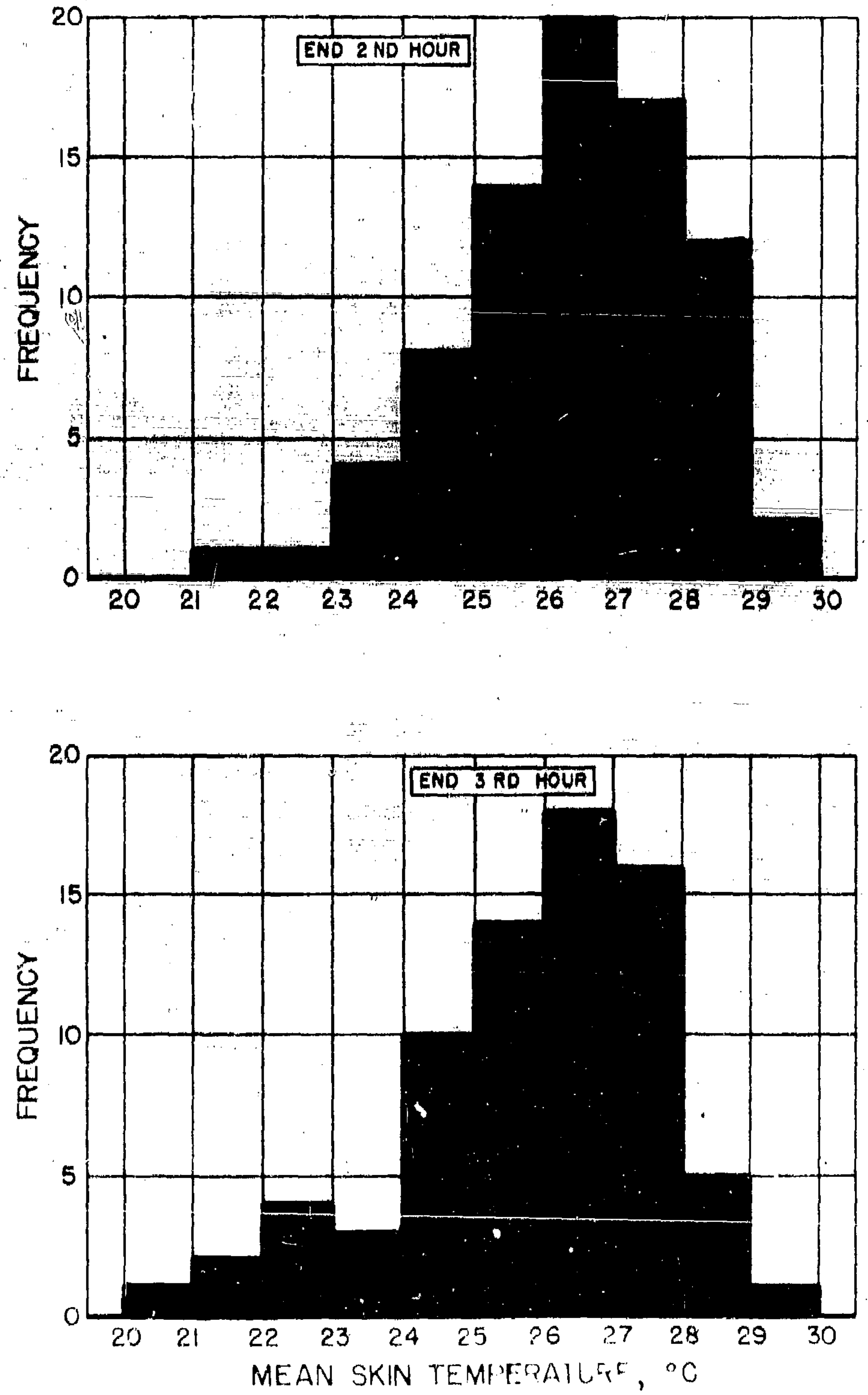

FIG. 2

FIG. 3

DISTRIBUTION OF TOE TEMPERATURES
AT END OF 2 ND AND 3 RD HOURS EXPOSURE
AMBIENT TEMPERATURE -23° TO -29° C
41 SUBJECTS

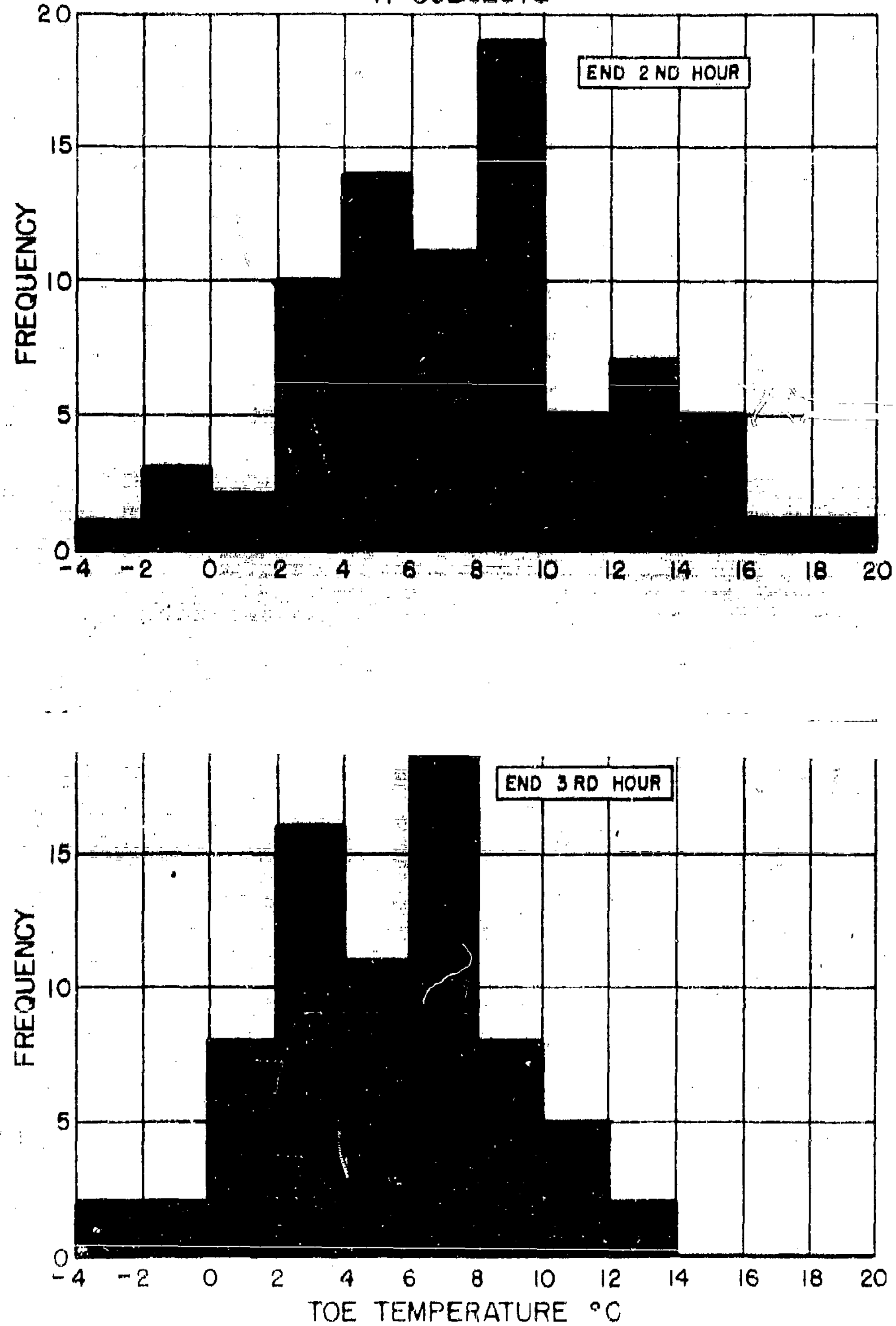

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FIG. 3

FIG. 4

DISTRIBUTION OF EXPOSURE TIME TO ONSET OF PAIN
AND COINCIDENT TOE TEMPERATURES
AMBIENT TEMPERATURE -23° TO -29° C
41 SUBJECTS

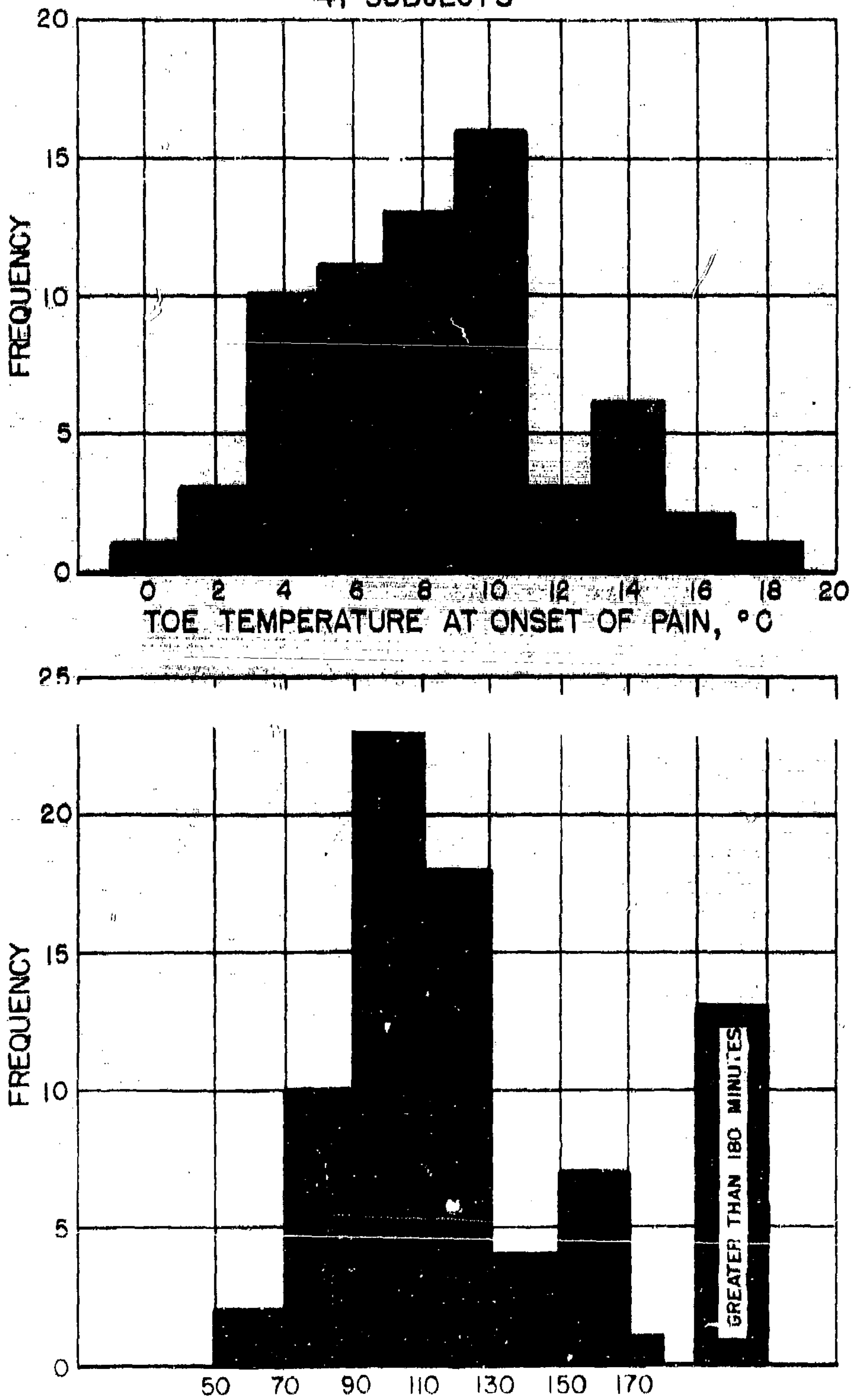


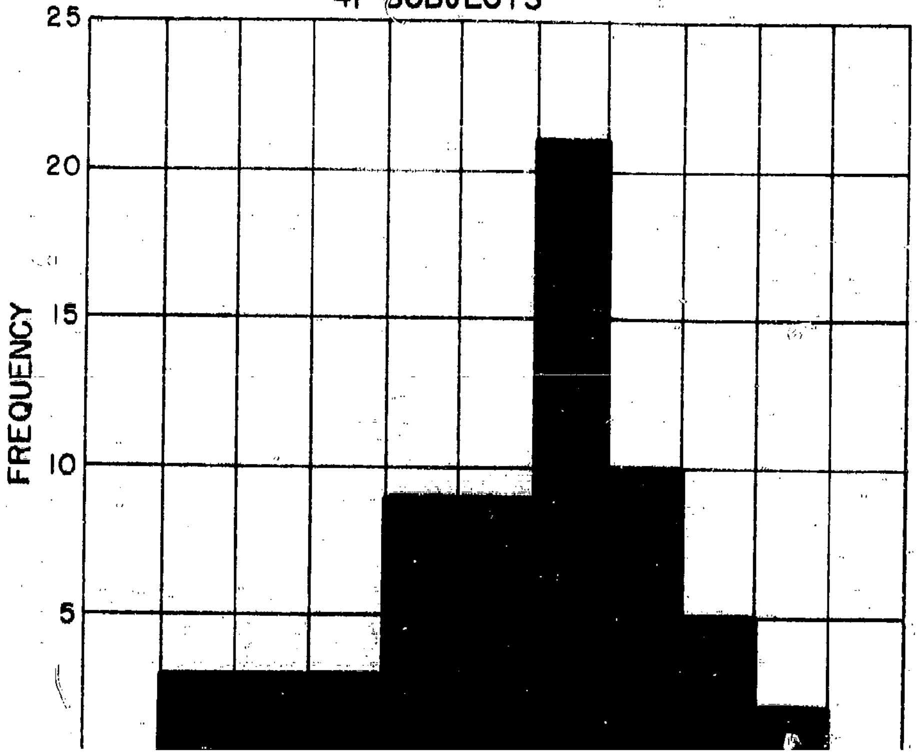
FIG. 4

FIG. 5

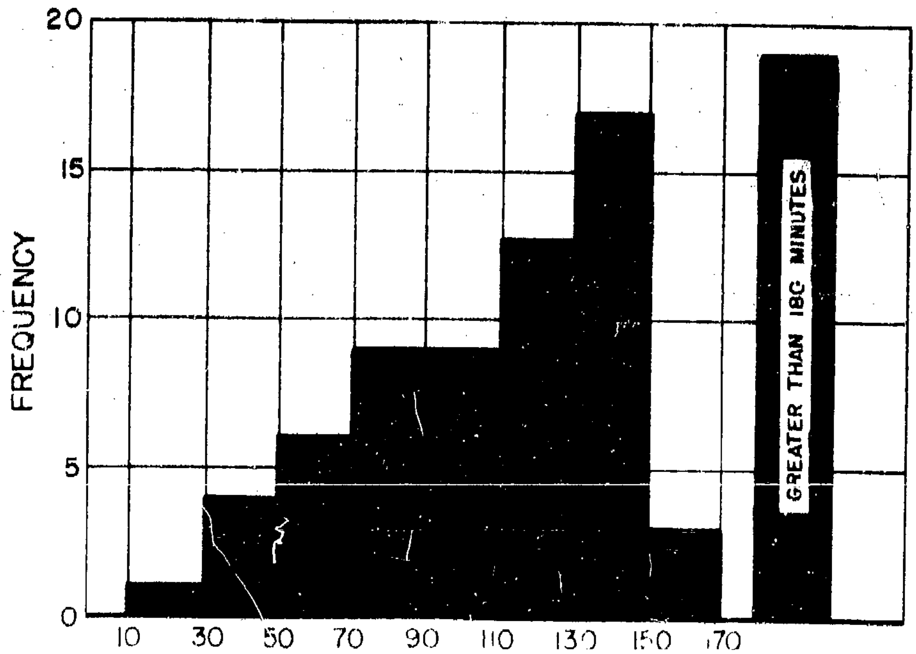
DISTRIBUTION OF EXPOSURE TIME TO ONSET OF SHIVERING
AND COINCIDENT MEAN SKIN TEMPERATURE

AMBIENT TEMPERATURE -23° TO -29° C

41 SUBJECTS



MEAN SKIN TEMPERATURES AT ONSET OF SHIVERING, °C



TIME OF EXPOSURE TO ONSET OF SHIVERING, MINUTES

FIG. 5

FIG. 6

INFLUENCE OF CHANGE IN BODY HEAT CONTENT UPON CALCULATED CLOTHING INSULATION

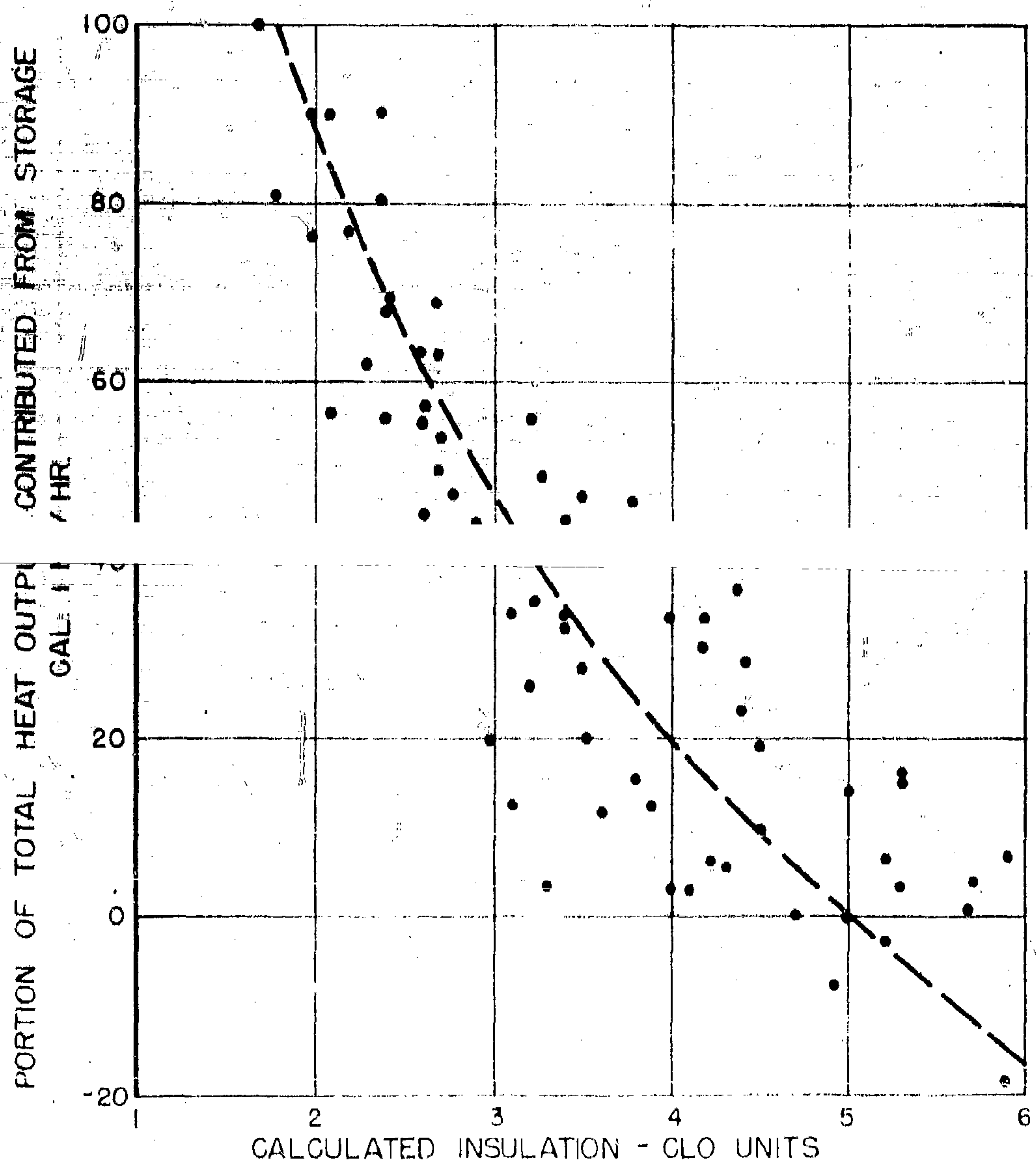


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FIG. 6

FIG. 7

CHANGES IN MEAN SKIN AND TOE TEMPERATURES IN RELATION TO INITIAL THERMAL CONDITION OF CLOTHING

5 SUBJECTS, EXPOSURE TEMPERATURE, - 26° C

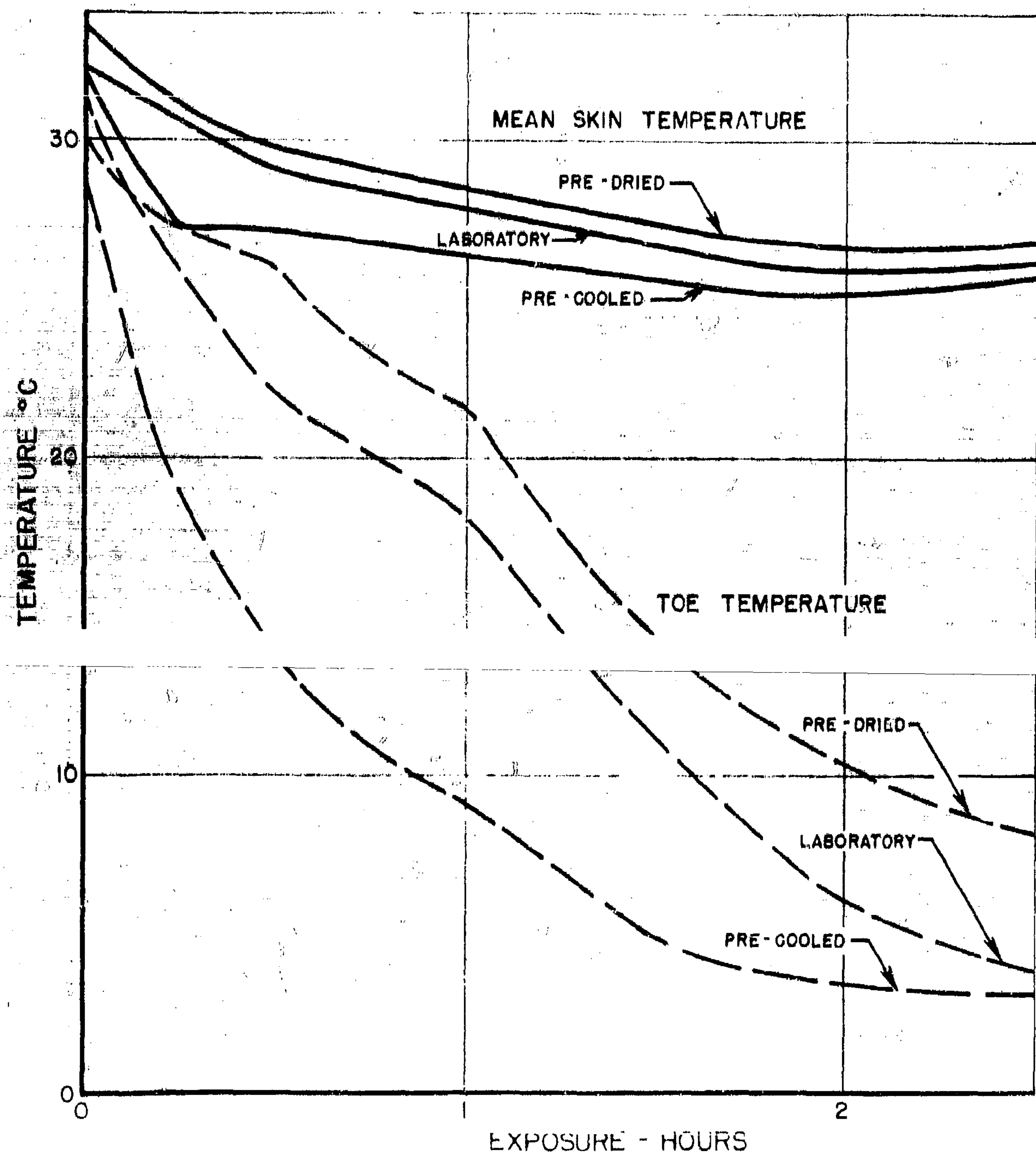

FIG. 7

FIG. 8

TYPICAL TIME - TEMPERATURE PLOT
$\theta_S - \theta_E$ VS EXPOSURE TIME

SUBJECT BR

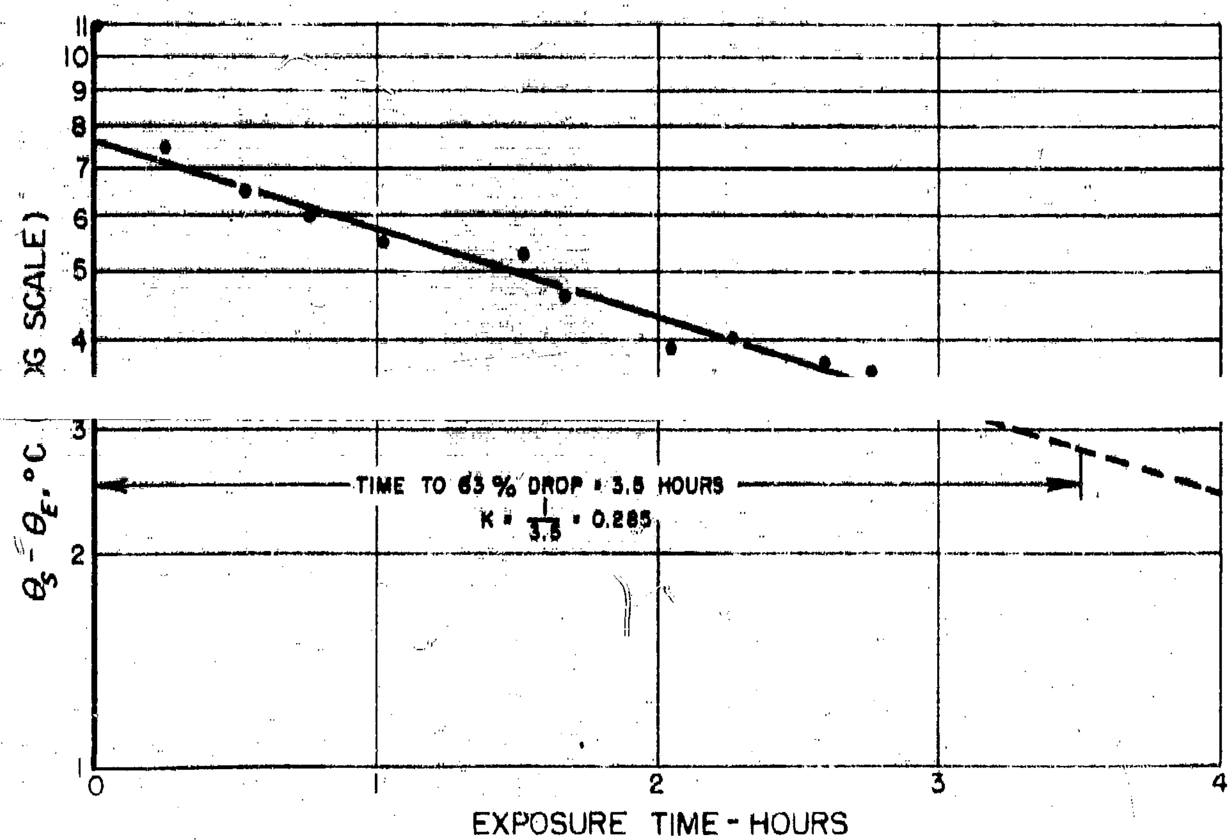

FIG. 8

FIG. 9

DISTRIBUTION OF COOLING CONSTANTS (K)

41 SUBJECTS

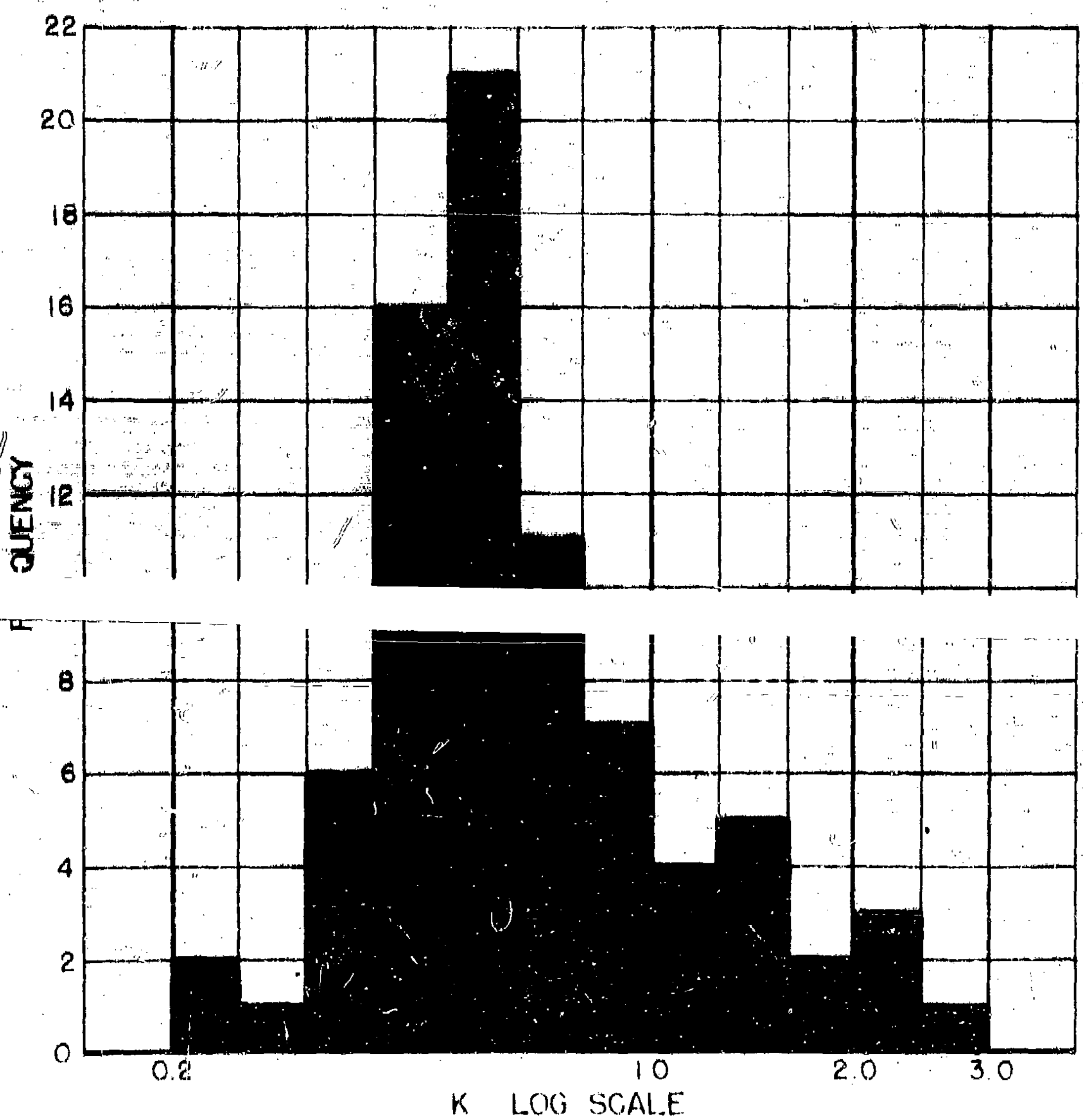

FIG. 9

FIG. 10

TEST - RETEST RELATION OF COOLING CONSTANT (K)

41 SUBJECTS

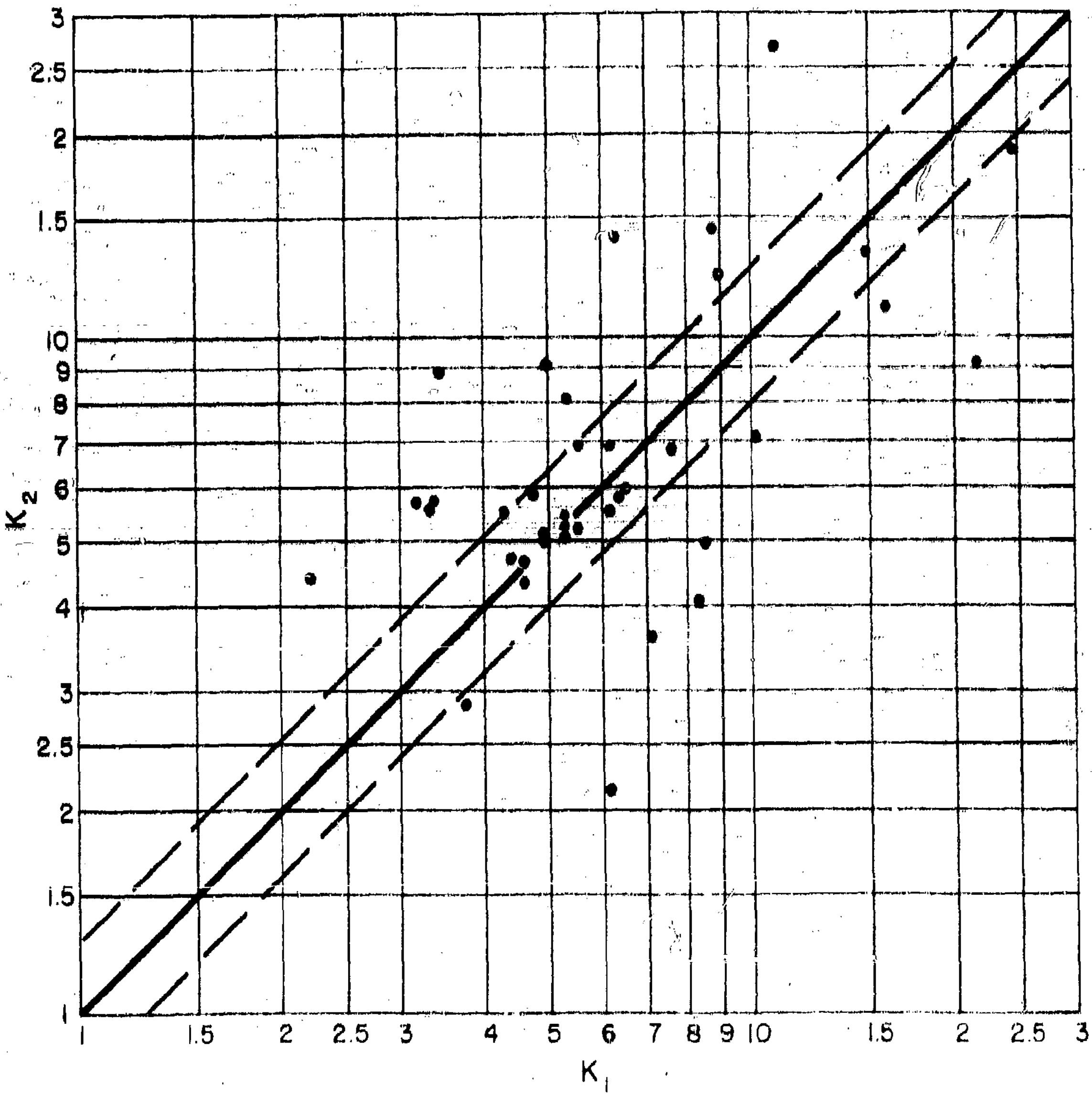

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FIG. 10